AC 2008-1509: KINESTHETIC STRUCTURES

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Kinesthetic Structures

Abstract

This paper describes how students are engaged in hands-on activities that reinforce complex engineering principles. In addition to utilizing chalk board examples for design and analysis problems, physical modeling, not necessarily traditional laboratory testing, is implemented to link engineering theory with building behavior. Students design, build, and learn how structures behave in three dimensions.

Introduction

Five years ago, the author switched careers and from practice to academia. After teaching classes the traditional way, class lectures augmented with textbook homework, a program was developed to engage students in model building activities that encouraged creativity, promoted ownership in student learning, linked physical behavior to mathematical expressions, and hopefully better prepares students for engineering practice.[1]

Students in the college begin hands-on learning during their freshman year and this served as the impetus to link kinesthetic learning with lower level and upper level engineering courses. Students often list a junior level class as their favorite class because it incorporates model building projects into the curriculum. Students are often eager to work on these projects and are typically proud to show you what they have created. The goal was to capture this enthusiasm and pride of ownership when developing projects that excite students about structural engineering and marry engineering principles with physical behavior through the use of models. Additional challenges were to create assignments that;

- could be economically constructed
- could be constructed in class or as short homework assignments
- presented learning outcomes that were applicable to our departmental mission
- addressed construct-ability or cost issues

It is common for schools to use physical models to demonstrate concrete beam behavior or steel beam behavior, but the focus of the activities is to create physical models that help describe structural behavior in 3D, construction sequencing, structural detailing, etc. An ancillary goal is to show how these issues are included in the design process, from architectural design to structural design, and that the thought process is not linear but all of these decisions are addressed simultaneously. The use of physical models has been a success in the classroom, students have become interested in the topics since the topics now have a relevancy they didn't before, and students are beginning to see the creative side to structures that can be incorporated into their design projects.

Ideas

The typical engineering student at our campus is required to enroll in eighteen structures based courses, a fairly even mix of analytical and design based courses. The curriculum prepares students for the building industry so graduates are aware of structures related topics, but also those of other associated disciplines. When working on a project, students should be cognizant of design, engineering, as well as, constructability so a viable solution is developed. The use of models is one way of infusing these topics into the curriculum.

A number of model making activities have been developed for sophomore through senior year engineering courses that integrate design and construction issues. A sample of the activities is noted below:

- Arch and truss behavior
- Load path, framing plans, and deflection
- Center of mass, center of rigidity, and earthquakes
- Retaining walls, concrete formwork, and construction sequencing
- Design, detail, and build a connection competition

With the exception of the retaining wall activity, the models are constructed with materials found at the local hobby store; wooden dowels, hot glue, string, and cardboard. A typical assignment involves a short qualitative discussion about the behavioral issues being discovered and then construction of a model. For assignments that have multiple or "incremental" submittals, meetings are scheduled to ensure the student has an understanding of the deliverables and more importantly the learning objectives for that phase of the activity. Upon completion of the model, students are then given rigorous calculation based homework to reinforce the engineering principle discovered in the model making phase.

The activities are designed to demonstrate elementary principles associated with statics as well as more complex principle associated with building behavior. The activities are developed to make abstract concepts real by participating in qualitative experiments and contests. Students are also exposed to design and construction, but from a practitioner's perspective where the learning objectives are not to become an architectural designer or a builder, but to become a productive member of a design or construction team. Able to propose solutions that address the underlying principals of structures and address constructability and sequencing issues, but also provide thought provoking ideas about are sensitive to form and materiality.

Sophomores

In the second year, students enroll in two courses, Statics and Strength of Materials, which are primarily theory based, so the primary goal is to keep students interested in a structures topic in a way that caters to their learning strengths. Over the past three years the VARK™ survey has been administered on the first day of class and the results are similar from year to year. (The VARK™ acronym is short for Visual, Audio, Reading, and Kinesthetic learning.)[2] Over 75% of the participants learn best using kinesthetic, visual, or a combination of the two methods. The amazing result is that a typical class will have less than 5% of students who think they learn best by audio delivery or lecture. While lecturing is a mainstay of traditional education, this survey reinforces the proposition to use more visual and kinesthetic or hands on methods in class.

Another key aspect to using models in the classroom is to demonstrate physical phenomenon first and to reinforce those concepts using theory second. Normally, students build and break a model or build a project, then push and pull on it to understand the way the building will behave when exposed to the forces of nature. After the activity, the principles underlying the activity are explained in more detail to reinforce the concept that was demonstrated previously. Again, the goals are to enable students to better understand the global context of structures, to use methods that motivate the students, and to present material in a manner that the students learn best.

Students begin the structures sequence in their second year. As noted earlier, the first two courses are primarily analytical based. In a nutshell, the two courses can be summarized as classes that emphasizes stability, things that stretch, things that compress, and things that bend. The activities developed for these courses are relatively simple and easy to construct, but based on student feedback the model making has strengthened there understanding of the material. As an example, students are introduced to stability and statics using an exercise called the point, the line, the plane, and the mass. (Figure 1) Students are first required to develop a system to stabilize a shape and then quantify it second. The goal is two fold, one to understand the concept of stability or how things stand up and secondly to explain how these basic shapes are extrapolated to real world items, such as a beam or column for the line, a floor for the plane, and a building for the block. The students are also exposed to tension members such as string, compression/tension members such as sticks, how systems are formed using these types of elements, and the concept of buckling for members under compression.

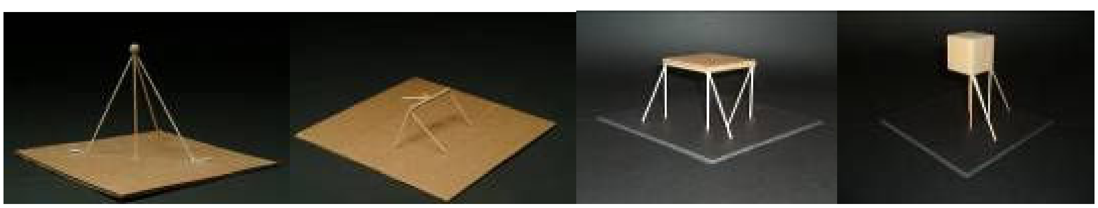

Figure1: Point, Line and Plane Series

<u>Juniors</u>

By their third year, students are immersed in framing schemes, structural system types, system behavior, and developing a load path for various building formations. Another goal for the third year student is learning how structure can be used to help inform the space, help create form, and the synergy that can exist between structure and architecture. In the structural systems course, student projects or models are developed to display how grid patterns can be used to create large volumes, articulate circulation, and create intersections of interest.[3] The model making process also serves as a means for students to understand labor cost, sequencing, and detailing in a broad context. As an example, when students analyze a truss, they discover that a truss will work as long as triangulation is completed along the length of the member, but when they have to build the truss, they soon realize that a truss with fewer diagonals or panels will work and requires less time or money to construct. The images shown in Figure 2 show student work for the two main projects: developing and constructing a truss model and developing and constructing a post and beam model. In each of these models, students develop a space that exhibits a combination of structure and architecture that is harder to achieve when in a lecture based curriculum. The students work in pairs and prepare a preliminary massing or framing model before proceeding with their presentation model. During the "preliminary model" phase students are required to explain how their proposed structure resists vertical loads such as dead and live loads and how the proposed building resists loads in the horizontal direction from wind or earthquake. No numbers, but the student are required to trace how loads track to the ground for their structural system and what are the approximate depths for the members based on rules of thumb. In a typical meeting, the students and the instructor push and pull on the model to mimic how the building is loaded and how it will displace. During these sessions, students discover where members need to be added at the floor or roof to create a diaphragm, where additional bracing is required to make the system stable, or where additional members are required to complete the load path, and general feedback about how the system can be arranged to make a flexible space. The most common comment is that the students felt they learned the most during these sessions because they were pushing on the model and receiving instant feedback on their work. When the course is finished students are comfortable with the three main building systems – braces and trusses, shear walls, and moment frames – and how these structural systems are incorporated into buildings in 3 dimensions.

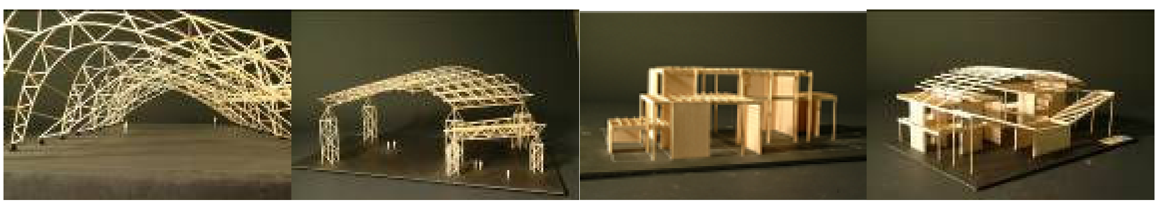

Figure 2: Structural Systems Series

When compared to the other courses in the curriculum, this course tends to be a favorite among the students. It goes without saying, that student evaluations have been very positive for this course, in large part because of the model building. Models have not been used for model building sake, but the use of models is a valuable tool which enables students to better understand structural behavior and how the structure can be used to develop space.

Even on a smaller scale, models are valuable in conveying the 3D concept of building torsion and the placement of shear walls or braced frames. A model constructed from cardboard and foam is used to help students understand why shear walls or braced frames are placed uniformly through out a building rather than stacked or concentrated in a particular area of the building. Students are taught the concept of stiffness, center of mass, and rotation – all abstract concepts if described verbally, but easily understood if demonstrated kinesthetically. Students are allowed to connect physical behavior with terms such as rigidity, building torsion, relative stiffness, and center of mass. The models also demonstrate how lateral load resisting systems impact design. A study was conducted between two classes comparing the understanding of classes before participating in the activity and after participating in the activity. The class that performed the activity scored twice as high as the class that did not participate in the activity and only received instruction in the typical lecture format. It was a compelling argument for using physical models to introduce and reinforce abstract engineering principles.

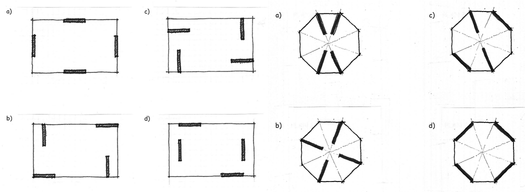

Figure 3: Center of rigidity and center of mass activity and concept questions

Seniors

By time students have reached their senior year they have been exposed to two structures based studios and a have completed eleven structures courses. The students are beginning to understand more about the building industry and the engineer's role in the design and construction process. Many of the students have worked as interns during the summer or are working part time in local consulting firms as CAD operators and student interns. Academically, the students begin to take classes that are design and practice oriented. Students enroll in three separate design studios where they design, analyze and create structural drawings for a timber framed building, a steel framed building, and a concrete framed building.

To stress the importance of detailing and construction sequencing students participate in an activity called "Build a Better Detail" in both steel design and concrete design studios. In the first year this activity was used, students acted as builders and were assigned a detail that was drawn by the instructor. Then the students built a model based on the information "submitted". Where information was missing and that information was necessary to construct the model, the construction team issued a request for information or RFI. This activity has been modified, based on student feedback, so that the students act as designers and draw the detail and then act as builders and construct the details so that they learn first hand what information is necessary to draw a construct-able detail. In the current form, students select a detail to draw from a set of conditions determined by the instructor. The students work in pairs and draw a small framing plan and then draw the connection detail. After the details are completed by each design team, the team "submits" the detail to another team for construction. At this point the teams change from design teams to construction teams. The teams issue RFI's when information is missing; such as a dimension, a clear distance, a call-out for bolts, welds, or reinforcement. Additionally, the details are "red-lined" by the instructor to show the students what information was missing or alternative ways to graphically communicate how to build. The RFI's also provide a medium for stressing written communication. It is common to see the design team and the construction team huddle in a "meeting" after an RFI was issued because it was unclear what issue needed additional clarification or the engineer's response was too vague for the contractor to proceed with the work. The RFI's are reviewed for content as well as grammar after the project is complete.

Students commonly state they were unaware how much information is required to draw a complete detail. They realize the importance of drawing to scale, showing material prep on steel shapes, the impact of bar bends and splices on reinforcement details, and the necessity for specifying the minute details of construction.

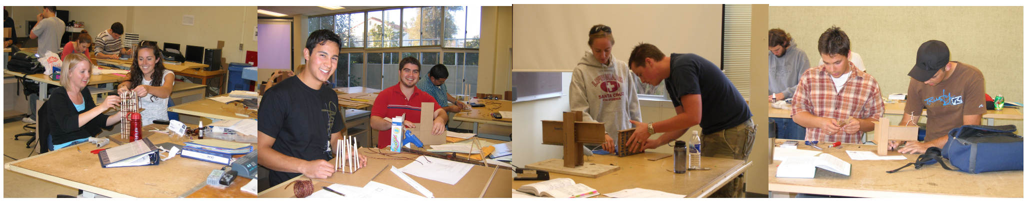

Figure 4: Build a Better Detail Activity

Electives

Students may also enroll in a foundation design class as an elective just prior to graduation. In this class students learn how to design both shallow and deep foundation and they also learn about constructability issues associated with these systems.

The final two week module is devoted to concrete construction with an emphasis on detailing, construction, and concrete finish. Student teams design and construct a concrete retaining wall on a plot of land two feet wide by four feet deep in an activity called "Hitting the Wall Competition". The student teams develop a design, create structural drawings, excavate the site, compact the soil, build the forms, and cast the concrete, they literally build the "structure" from the foundation up. The program calls for the student teams to create a retaining wall which retains one foot of soil, demonstrates a good example of concrete construction and form, and a prediction of the retaining wall failure mode. During the process students learn about the relationship between formwork and finish, formwork support and hydrostatic pressure, concrete finishing, tolerances, and reinforcement, and the impact construction can have on the retaining wall strength.

Student design teams first build a small scale model at one quarter scale, draw a foundation plan and submit their work for review. The models provide a vehicle to discuss concrete sequencing or concrete pour joint locations, stability issues, and general constructability issues. The drawings are produced to initiate students to the level of documentation required to build a structure. Wall locations need to be defined in plan, wall openings sized and located in elevation, wall thicknesses and lengths specified, etc. All information necessary to build the wall. Construction begins with excavating the site and soil compaction just like the real world. Footings are "earth" formed and cast. Starter dowels are used to tie the footing to the wall etc... Reinforcement and formwork inspections are conducted to ensure construction matches the structural drawings, and approval to proceed is granted when the work has been inspected and is found to conform to the construction documents, just like the real world. When the walls are poured, the concept of tying the structure together with reinforcement is highlighted and used as an example of how these concepts were discussed in pre requisite classes. The major hurdle for the student design-build teams is providing ample formwork bracing so that the hydrostatic pressure developed in the wet concrete does not cause the formwork to bulge out during concrete placing. One of the reasons for requiring twelve inches of retained soil is to provide a mechanism for the student teams to demonstrate and apply lessons learned from their previous courses dealing with concrete design, in this case lessons related to formwork, concrete placement, and concrete finishing.

After the walls are poured a building inspection is required and the teams produce as built drawings. This process helps reinforce the concept of building tolerances and that when detailing a structure the appropriate building tolerances need to be honored. Additionally the students need these dimensions to complete the next phase of the activity – the load test.

The final phase of the project ends with the students re-calculating the estimated capacity of the wall when loaded horizontally. The teams use the as-built dimensions to predict the failure load and failure mode for their projects. Interestingly, this latest step, re-calculating the failure load was a suggestion by an invited reviewer. This final step has helped bring closure in having the students understand building tolerances. After the predictions have been submitted, the walls are loaded as shown in Figure 5. A horizontal load is added to the lateral earth pressure exerted by the 12 inches of retained soil. The walls are loaded to failure and the team with the closest prediction wins a prize.

Design and construction decisions are addressed in every structure and in this exercise the students are exposed to the same design issues – just on a small scale. The students look forward to getting their hands dirty, creating something, and ultimately breaking something. Students have commented that they learned more about vertical and horizontal control, formwork, and concrete finishing than they would have learned by looking at slides or only listening to a lecture. There are many lessons going on simultaneously when building a model and can seem to be overwhelming, but student evaluations suggest the exposure to the full design and construction process is an unforgettable and enjoyable process.

Figure 5: Hitting the Wall Competition

Reflection

Most of the projects have been modified in response to student surveys. Student feedback has been instrumental in creating activities that students find engaging and fun to complete, but also meet the learning objectives for the course. Based on student feedback, the model making phase is the most popular portion of a given class and the students credit the activities with their success in understanding the learning objectives.

The premise of change in academia is to consider the way students learn and to match that process with topics they need to know when they graduate. Additionally, the material should be presented in a manner that will engage the students. The solution at our institution was to develop a series of activities that rely on physical models to demonstrate abstract structural concepts, demonstrate the integration with architecture, and demonstrate constructability issues.

Preparing students for the working world requires graduates to be versed in both traditional engineering theory and design. But that is only part of the body of knowledge required to be productive in the building profession. Students need to know how engineering is applied in the practical world, how engineering informs architecture, how engineering is linked with construction, and how engineering relies on communication. When students are aware of the integration between disciplines, they can suggest thoughtful design proposals for building projects. The use of models and our student's propensity for kinesthetic learning allows them to acquire an in depth understanding of the principles driving a design, but also a working knowledge of the way things work in real structures. The goal of these activities is to help mesh the physical world with the analytical world of engineering. And based on both student and alumni feedback, the models played a significant role in their learning process.

It is the hope of the author that using models helps students better understand structures and better understand the role of the architectural engineer. There is no scientific method to proclaim this is the answer for training young architectural engineering minds about structures and building technology, but in all of the courses the students become engaged when they work with their hands and minds in a creative environment. And personally, this is the first hurdle to learning. If these classes were taught in a pure lecture setting, topics such as tolerances and concrete finishes could be discussed, but the real meaning of the term is lost unless one can see it applied in a real world situation. After completing the sequence, the student evaluations indicate the highest learning came with the hands-on activities and the activities gave the students confidence in their ability to understand the principles and design issues presented in class. The course sequence has become such a success that students often ask which models we will build in class when we begin the term.

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I would also like to thank the architectural engineering department and the college of design for providing a collegial setting and encouraging new faculty like myself to conduct a series of courses that meet the needs of the students and meet the visions of the faculty member.

Bibliography

1. Dong, K, "Making Statics a Friend for Life", 2006 ASEE Annual Conference and Exposition Proceedings, ASEE, Chicago, June 2006.
2. VARK: a guide to learning styles, *http:/www.vark-learn.com*
3. Feldman, Jake, *Structural Systems: ARCE 371 Notes and Information*, Spring 2000